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# WW Physics at Future $e^+e^-$ Linear Colliders

TIMOTHY L. BARKLOW\*

*Stanford Linear Accelerator Center  
Stanford, California 94309, USA*

Measurements of triple gauge boson couplings and strong electroweak symmetry breaking effects at future  $e^+e^-$  linear colliders are reviewed. The results expected from a future  $e^+e^-$  linear collider are compared with LHC expectations.

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## 1 Introduction

The measurement of gauge boson self-couplings at a future  $e^+e^-$  collider will provide insight into new physics processes in the presence or absence of new particle production. In the absence of particle resonances, and in particular in the absence of a Higgs boson resonance, the measurement of gauge boson couplings will provide a window to the new physics responsible for electroweak symmetry breaking. If there are many new particles being produced – if, for example, supersymmetric particles abound – then the measurement of gauge boson couplings will prove valuable since the gauge boson couplings will reflect the properties of the new particles through radiative corrections.

Experiments at LEP2 have demonstrated the viability of measuring gauge boson self-couplings at an  $e^+e^-$  collider. Complex effects such as initial and final state radiation,  $\mathcal{O}(\alpha)$  electroweak radiative corrections, fragmentation, and detector bias are incorporated into analyses which utilize all decay modes of the  $W$  boson. The present LEP2 triple gauge boson precision of a few percent [1] exceeds the predictions for LEP2 sensitivity made a decade ago.

In this paper we review the prospect for studying triple gauge boson couplings and strong electroweak symmetry breaking effects at future  $e^+e^-$  linear colliders. We will deal primarily with the reaction  $e^+e^- \rightarrow W^+W^-$ . However, when discussing strong electroweak symmetry breaking we will also consider the processes  $e^+e^- \rightarrow \nu\bar{\nu}W^+W^-$ ,  $\nu\bar{\nu}ZZ$ , and  $\nu\bar{\nu}t\bar{t}$ . Triple gauge boson production is important for the study of quartic gauge boson couplings, but is beyond the scope of this paper.

## 2 Triple gauge boson couplings

Gauge boson self-couplings include the triple gauge couplings (TGCs) and quartic gauge couplings (QGCs) of the photon,  $W$  and  $Z$ . Of special importance at a linear collider are the  $WW\gamma$  and  $WWZ$  TGCs since a large sample of fully reconstructed  $e^+e^- \rightarrow W^+W^-$  events will be available to measure these couplings.

The effective Lagrangian for the general  $W^+W^-V$  vertex ( $V = \gamma, Z$ ) contains 7 complex TGCs, denoted by  $g_1^V$ ,  $\kappa_V$ ,  $\lambda_V$ ,  $g_4^V$ ,  $g_5^V$ ,  $\tilde{\kappa}_V$ , and  $\tilde{\lambda}_V$  [2]. The magnetic dipole and electric quadrupole moments of the  $W$  are linear combinations of  $\kappa_\gamma$  and  $\lambda_\gamma$  while the magnetic quadrupole and electric dipole moments are linear combinations of  $\tilde{\kappa}_\gamma$  and  $\tilde{\lambda}_\gamma$ . The TGCs  $g_1^V$ ,  $\kappa_V$ , and  $\lambda_V$  are C– and P–conserving,  $g_5^V$  is C– and P-violating but conserves CP, and  $g_4^V$ ,  $\tilde{\kappa}_V$ , and  $\tilde{\lambda}_V$  are CP-violating. In the SM at tree-level all the TGCs are zero except  $g_1^V = \kappa_V = 1$ .

If there is no Higgs boson resonance below about 800 GeV, the interactions of the  $W$  and  $Z$  gauge bosons become strong above 1 TeV in the  $WW$ ,  $WZ$  or  $ZZ$  center-of-mass system. In analogy with  $\pi\pi$  scattering below the  $\rho$  resonance, the

interactions of the  $W$  and  $Z$  bosons below the strong symmetry breaking resonances can be described by an effective chiral Lagrangian [3]. These interactions induce anomalous TGC's at tree-level:

$$\begin{aligned}\kappa_\gamma &= 1 + \frac{e^2}{32\pi^2 s_w^2} (L_{9L} + L_{9R}) \\ \kappa_Z &= 1 + \frac{e^2}{32\pi^2 s_w^2} \left( L_{9L} - \frac{s_w^2}{c_w^2} L_{9R} \right) \\ g_1^Z &= 1 + \frac{e^2}{32\pi^2 s_w^2} \frac{L_{9L}}{c_w^2},\end{aligned}$$

where  $s_w^2 = \sin^2 \theta_w$ ,  $c_w^2 = \cos^2 \theta_w$ , and  $L_{9L}$  and  $L_{9R}$  are chiral Lagrangian parameters. If we replace  $L_{9L}$  and  $L_{9R}$  by the values of these parameters in QCD,  $\kappa_\gamma$  is shifted by  $\Delta\kappa_\gamma \sim -3 \times 10^{-3}$ .

Standard Model radiative corrections [4] cause shifts in the TGCs of  $\mathcal{O}(10^{-4} - 10^{-3})$  for CP-conserving couplings and of  $\mathcal{O}(10^{-10} - 10^{-8})$  for CP-violating TGC's. Radiative corrections in the MSSM can cause shifts of  $\mathcal{O}(10^{-4} - 10^{-2})$  in both the CP-conserving [5] and CP-violating TGC's [6].

The methods used at LEP2 to measure TGCs provide a useful guide to the measurement of TGCs at a linear collider. When measuring TGCs the kinematics of an  $e^+e^- \rightarrow W^+W^-$  event can be conveniently expressed in terms of the  $W^+W^-$  center-of-mass energy following initial state radiation (ISR), the masses of the  $W^+$  and  $W^-$ , and five angles: the angle between the  $W^-$  and initial  $e^-$  in the  $W^+W^-$  rest frame, the polar and azimuthal angles of the fermion in the rest frame of its parent  $W^-$ , and the polar and azimuthal angles of the anti-fermion in the rest frame of its parent  $W^+$ .

In practice not all of these variables can be reconstructed unambiguously. For example, in events with hadronic decays it is often difficult to measure the flavor of the quark jet, and so there is usually a two-fold ambiguity for quark jet directions. Also, it can be difficult to measure ISR and consequently the measured  $W^+W^-$  center-of-mass energy is often just the nominal  $\sqrt{s}$ . Monte Carlo simulation is used to account for detector resolution, quark hadronization, initial- and final-state radiation, and other effects.

The TGC measurement error at a linear collider can be estimated to a good approximation by considering  $e\nu q\bar{q}$  and  $\mu\nu q\bar{q}$  channels only, and by ignoring all detector and radiation effects except for the requirement that the  $W^+W^-$  fiducial volume be restricted to  $|\cos\theta_W| < 0.9$ . Such an approach correctly predicts the TGC sensitivity of LEP2 experiments and of detailed linear collider simulations [7]. This rule-of-thumb approximation works because LEP2 experiments and detailed linear collider simulations also use the  $\tau\nu q\bar{q}$ ,  $\ell\nu\ell\nu$  and  $q\bar{q}q\bar{q}$  channels, and the increased sensitivity from these extra channels makes up for the lost sensitivity due to detector resolution, initial- and final-state radiation, and systematic errors.

TGC	error $\times 10^{-4}$			
	$\sqrt{s} = 500 \text{ GeV}$		$\sqrt{s} = 1000 \text{ GeV}$	
	Re	Im	Re	Im
$g_1^\gamma$	15.5	18.9	12.8	12.5
$\kappa_\gamma$	3.5	9.8	1.2	4.9
$\lambda_\gamma$	5.4	4.1	2.0	1.4
$g_1^Z$	14.1	15.6	11.0	10.7
$\kappa_Z$	3.8	8.1	1.4	4.2
$\lambda_Z$	4.5	3.5	1.7	1.2

Table 1: Expected errors for the real and imaginary parts of CP-conserving TGCs assuming  $\sqrt{s} = 500 \text{ GeV}$ ,  $\mathcal{L} = 500 \text{ fb}^{-1}$  and  $\sqrt{s} = 1000 \text{ GeV}$ ,  $\mathcal{L} = 1000 \text{ fb}^{-1}$ . The results are for one-parameter fits in which all other TGCs are kept fixed at their SM values.

TGC	error $\times 10^{-4}$			
	$\sqrt{s} = 500 \text{ GeV}$		$\sqrt{s} = 1000 \text{ GeV}$	
	Re	Im	Re	Im
$\tilde{\kappa}_\gamma$	22.5	16.4	14.9	12.0
$\tilde{\lambda}_\gamma$	5.8	4.0	2.0	1.4
$\tilde{\kappa}_Z$	17.3	13.8	11.8	10.3
$\tilde{\lambda}_Z$	4.6	3.4	1.7	1.2
$g_4^\gamma$	21.3	18.8	13.9	12.8
$g_5^\gamma$	19.3	21.6	13.3	13.4
$g_4^Z$	17.9	15.2	12.0	10.4
$g_5^Z$	16.0	16.7	11.4	10.7

Table 2: Expected errors for the real and imaginary parts of C- and P-violating TGCs assuming  $\sqrt{s} = 500 \text{ GeV}$ ,  $\mathcal{L} = 500 \text{ fb}^{-1}$  and  $\sqrt{s} = 1000 \text{ GeV}$ ,  $\mathcal{L} = 1000 \text{ fb}^{-1}$ . The results are for one-parameter fits in which all other TGCs are kept fixed at their SM values.

Table 1 contains the estimates of the TGC precision that can be obtained at  $\sqrt{s} = 500$  and  $1000 \text{ GeV}$  for the CP-conserving couplings  $g_1^V$ ,  $\kappa_V$ , and  $\lambda_V$ . These estimates are derived from one-parameter fits in which all other TGC parameters are kept fixed at their tree-level SM values. Table 2 contains the corresponding estimates for the C- and P-violating couplings  $\tilde{\kappa}_V$ ,  $\tilde{\lambda}_V$ ,  $g_4^V$ , and  $g_5^V$ . An alternative method of measuring the  $WW\gamma$  couplings is provided by the channel  $e^+e^- \rightarrow \nu\bar{\nu}\gamma$  [8].

The difference in TGC precision between the LHC and a linear collider depends on

the TGC, but typically the TGC precision at the linear collider will be substantially better, even at  $\sqrt{s} = 500$  GeV. Figure 1 shows the measurement precision expected for the LHC [9] and for linear colliders of three different energies for four different TGCs.

If the goal of a TGC measurement program is to search for the first sign of deviation from the SM, then one-parameter fits in which all other TGCs are kept fixed at their tree-level SM values are certainly appropriate. But what if the goal is to survey a large number TGCs, all of which seem to deviate from their SM value? Is a 28-parameter fit required? The answer is probably no, as illustrated in Fig. 2.

Figure 2 shows the histogram of the correlation coefficients for all 171 pairs of TGCs when 19 different TGCs are measured at LEP2 using one-parameter fits. The entries in Fig. 2 with large positive correlations are pairs of TGCs that are related to each other by the interchange of  $\gamma$  and  $Z$ . The correlation between the two TGCs of each pair can be removed using the dependence on electron beam polarization. The entries in Fig. 2 with large negative correlations are TGC pairs of the type  $Re(\tilde{\kappa}_\gamma)/Re(\tilde{\lambda}_\gamma)$ ,  $Re(\tilde{\kappa}_Z)/Re(\tilde{\lambda}_Z)$ , etc. Half of the TGC pairs with large negative correlations will become uncorrelated once polarized electron beams are used, leaving only a small number of TGC pairs with large negative or positive correlation coefficients.

### 3 Strong WW scattering

Strong  $W^+W^-$  scattering can be studied at a linear collider with the reactions  $e^+e^- \rightarrow \nu\bar{\nu}W^+W^-$ ,  $\nu\bar{\nu}ZZ$ ,  $\nu\bar{\nu}t\bar{t}$ , and  $W^+W^-$  [10]. The final states  $\nu\bar{\nu}W^+W^-$ ,  $\nu\bar{\nu}ZZ$  are used to study the  $I=J=0$  channel in  $W^+W^-$  scattering, while the final state  $W^+W^-$  is best-suited for studying the  $I=J=1$  channel. The  $\nu\bar{\nu}t\bar{t}$  final state can be used to investigate strong electroweak symmetry breaking in the fermion sector through the process  $W^+W^- \rightarrow t\bar{t}$ .

The first step in studying strong  $W^+W^-$  scattering is to separate the scattering of a pair of longitudinally polarized  $W$ 's, denoted by  $W_L W_L$ , from transversely polarized  $W$ 's, and from background such as  $e^+e^- \rightarrow e^+e^-W^+W^-$  and  $e^-\bar{\nu}W^+Z$ . Studies have shown that simple cuts can be used to achieve this separation in  $e^+e^- \rightarrow \nu\bar{\nu}W^+W^-$ ,  $\nu\bar{\nu}ZZ$  at  $\sqrt{s} = 1000$  GeV, and that the signals are comparable to those obtained at the LHC [11]. Furthermore, by analyzing the gauge boson production and decay angles it is possible to use these reactions to measure chiral Lagrangian parameters with an accuracy greater than that which can be achieved at the LHC [12].

The reaction  $e^+e^- \rightarrow \nu\bar{\nu}t\bar{t}$  provides unique access to  $W^+W^- \rightarrow t\bar{t}$  since this process is overwhelmed by the background  $gg \rightarrow t\bar{t}$  at the LHC. Techniques similar to those employed to isolate  $W_L W_L \rightarrow W^+W^-$ ,  $ZZ$  can be used to measure the enhancement in  $W_L W_L \rightarrow t\bar{t}$  production [13]. Even in the absence of a resonance it

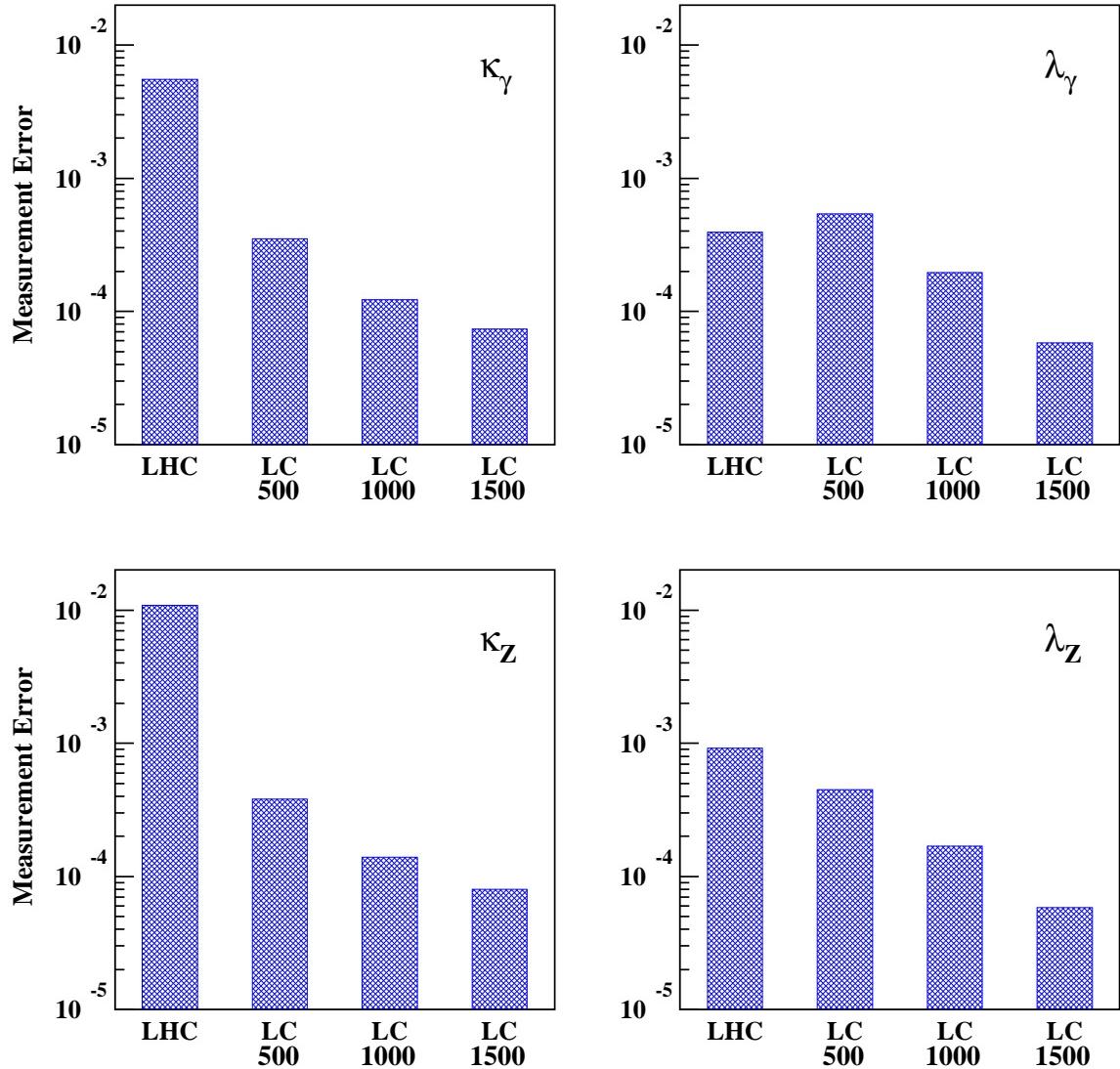


Figure 1: Expected measurement error for the real part of four different TGCs. The numbers below the “LC” labels refer to the center-of-mass energy of the linear collider in GeV. The luminosity of the LHC is assumed to be  $300 fb^{-1}$ , while the luminosities of the linear colliders are assumed to be  $500, 1000$ , and  $1000 fb^{-1}$  for  $\sqrt{s}=500, 1000$ , and  $1500$  GeV respectively.

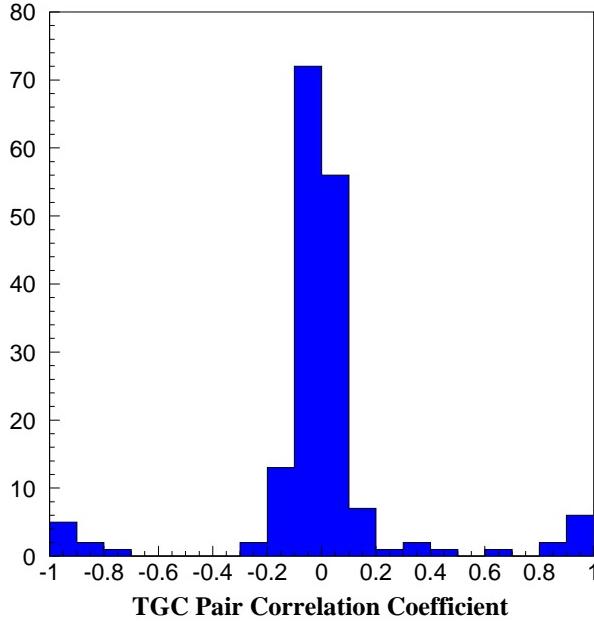


Figure 2: Histogram of correlation coefficients for all 171 pairs of TGCs when 19 different TGCs are measured using one-parameter fits at LEP2 (unpolarized beams). The 19 TGCs are made up of the real and imaginary parts of the 8 C- and P-violating couplings along with the real parts of the three CP-conserving couplings  $g_1^Z$ ,  $\kappa_\gamma$ ,  $\lambda_\gamma$ .

will be possible to clearly establish a signal. The ratio  $S/\sqrt{B}$  is expected to be 12 for a linear collider with  $\sqrt{s} = 1$  TeV and  $1000 \text{ fb}^{-1}$  and 80%/0% electron/positron beam polarization, increasing to 28 for the same data sample at  $\sqrt{s} = 1.5$  TeV.

There are two approaches to studying strong  $W^+W^-$  scattering with the process  $e^+e^- \rightarrow W^+W^-$ . The first approach was discussed in Section 2: a strongly coupled gauge boson sector induces anomalous TGCs which could be measured in  $e^+e^- \rightarrow W^+W^-$ . The precision of  $4 \times 10^{-4}$  for the TGCs  $\kappa_\gamma$  and  $\kappa_Z$  at  $\sqrt{s} = 500$  GeV can be interpreted as a precision of 0.26 for the chiral lagrangian parameters  $L_{9L}$  and  $L_{9R}$ . Assuming naive dimensional analysis [14], such a measurement would provide a  $8\sigma$  ( $5\sigma$ ) signal for  $L_{9L}$  and  $L_{9R}$  if the strong symmetry breaking energy scale were 3 TeV (4 TeV). The only drawback to this approach is that the detection of anomalous TGCs does not by itself provide unambiguous proof of strong electroweak symmetry breaking.

The second approach involves an effect unique to strong  $W^+W^-$  scattering. When  $W^+W^-$  scattering becomes strong the amplitude for  $e^+e^- \rightarrow W_L W_L$  develops a complex form factor  $F_T$  in analogy with the pion form factor in  $e^+e^- \rightarrow \pi^+\pi^-$  [15]. To

evaluate the size of this effect the following expression for  $F_T$  has been suggested:

$$F_T = \exp \left[ \frac{1}{\pi} \int_0^\infty ds' \delta(s', M_\rho, \Gamma_\rho) \left\{ \frac{1}{s' - s - i\epsilon} - \frac{1}{s'} \right\} \right]$$

where

$$\delta(s, M_\rho, \Gamma_\rho) = \frac{1}{96\pi} \frac{s}{v^2} + \frac{3\pi}{8} \left[ \tanh\left(\frac{s - M_\rho^2}{M_\rho \Gamma_\rho}\right) + 1 \right].$$

Here  $M_\rho, \Gamma_\rho$  are the mass and width respectively of a vector resonance in  $W_L W_L$  scattering. The term

$$\delta(s) = \frac{1}{96\pi} \frac{s}{v^2}$$

is the Low Energy Theorem (LET) amplitude for  $W_L W_L$  scattering at energies below a resonance. Below the resonance the real part of  $F_T$  is proportional to  $L_{9L} + L_{9R}$ , and can therefore be interpreted as a TGC. The imaginary part, however, is a distinctive new effect.

The real and imaginary parts of  $F_T$  are measured [16] in the same manner as the TGCs. The  $W^+W^-$  production and decay angles are analyzed and an electron beam polarization of 80% is assumed. In contrast to TGCs, the analysis of  $F_T$  seems to benefit from even small amounts of jet flavor tagging. We therefore assume that charm jets can be tagged with a purity/efficiency of 100/33%. These purity/efficiency numbers are based on research [17] which indicates that it may be possible to tag charm jets with a purity/efficiency as high as 100/65% given that  $b$  jet contamination is not a significant factor in  $W^+W^-$  pair-production and decay.

The expected 95% confidence level limits for  $F_T$  for  $\sqrt{s} = 500$  GeV and a luminosity of  $500 \text{ fb}^{-1}$  are shown in Fig. 3, along with the predicted values of  $F_T$  for various masses  $M_\rho$  of a vector resonance in  $W_L W_L$  scattering. The masses and widths of the vector resonances are chosen to coincide with those used in the ATLAS TDR [9]. The technipion form factor  $F_T$  affects only the amplitude for  $e^+e^- \rightarrow W_L W_L$ , whereas TGCs affect all amplitudes. Through the use of electron beam polarization and the rich angular information in  $W^+W^-$  production and decay, it will be possible to disentangle anomalous values of  $F_T$  from other anomalous TGC values and deduce the mass of a strong vector resonance well below threshold, as suggested by Fig. 3.

The signal significances obtained by combining the results for  $e^+e^- \rightarrow \nu\bar{\nu}W^+W^-$ ,  $\nu\bar{\nu}ZZ$  [11] with the  $F_T$  analysis of  $W^+W^-$  [16] are displayed in Fig. 4 along with the results expected from the LHC [9]. The LHC signal is a mass bump in  $W^+W^-$ ; the LC signal is less direct. Nevertheless, the signals at the LC are strong, particularly in  $e^+e^- \rightarrow W^+W^-$ , where the technirho effect gives a large enhancement of a very well-understood Standard Model process. Since the technipion form factor includes an integral over the technirho resonance region, the linear collider signal significance is relatively insensitive to the technirho width. (The real part of  $F_T$  remains fixed as the width is varied, while the imaginary part grows as the width grows.) The

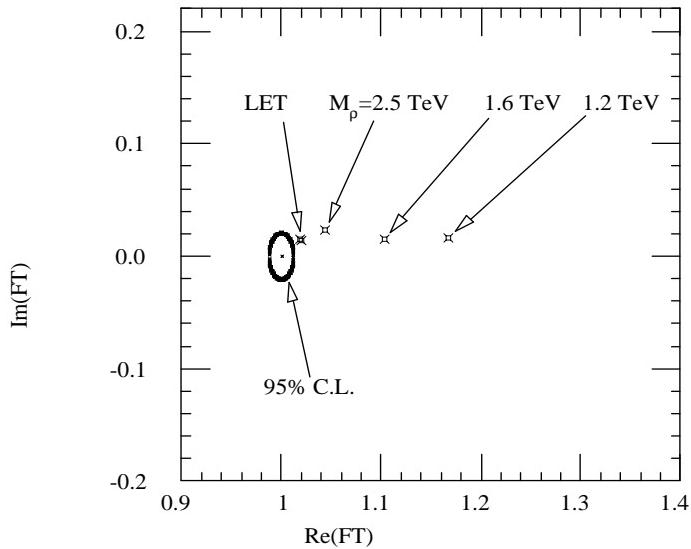


Figure 3: 95% C.L. contour for  $F_T$  for  $\sqrt{s} = 500$  GeV and  $500 fb^{-1}$ . Values of  $F_T$  for various masses  $M_\rho$  of a vector resonance in  $W_L W_L$  scattering are also shown. The  $F_T$  point “LET” refers to the case where no vector resonance exists at any mass in strong  $W_L W_L$  scattering.

LHC signal significance will drop as the technirho width increases. The large linear collider signals can be utilized to study a vector resonance in detail; for example, the evolution of  $F_T$  with  $\hat{s}$  can be determined by measuring the initial state radiation in  $e^+e^- \rightarrow W^+W^-$ .

Only when the vector resonance disappears altogether (the LET case in the lower right-hand panel in Fig. 4 ) does the direct strong symmetry breaking signal from the  $\sqrt{s} = 500$  GeV linear collider drop below the LHC signal. At higher  $e^+e^-$  center-of-mass energies the linear collider signal exceeds the LHC signal.

## 4 Conclusion

A future  $e^+e^-$  linear collider operating in the center-of-mass energy range of  $0.5 - 1.0$  TeV will measure TGCs with an accuracy of order  $10^{-4}$ , which corresponds to an improvement of two orders of magnitude over present LEP2 measurements and one order of magnitude over what is expected from the LHC. Such a precision is sufficient to test electroweak radiative corrections to the TGCs.

Studies of strong electroweak symmetry breaking are enhanced by a future  $e^+e^-$  linear collider. Signal and background in  $WW$  scattering are limited to electroweak processes, so that a measurement of a structureless enhancement in the total  $WW$

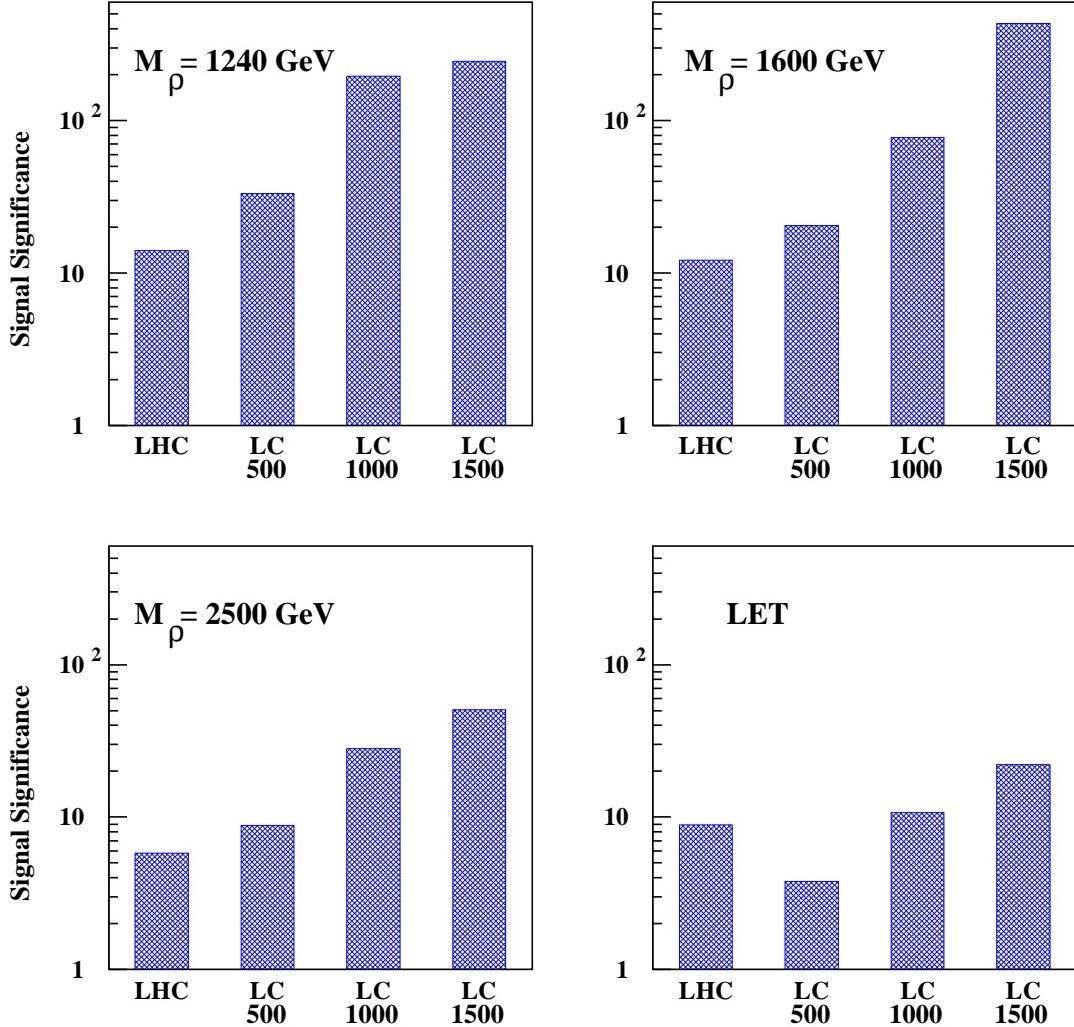


Figure 4: Direct strong symmetry breaking signal significance in  $\sigma$ 's for various masses  $M_\rho$  of a vector resonance in  $W_L W_L$  scattering. In the first three plots the signal at the LHC is a bump in the  $WW$  cross section; in the LET plot, the LHC signal is an enhancement over the SM cross section. The various LC signals are for enhancements of the amplitude for pair-production of longitudinally polarized  $W$  bosons. The numbers below the “LC” labels refer to the center-of-mass energy of the linear collider in GeV. The luminosity of the LHC is assumed to be  $300 \text{ fb}^{-1}$ , while the luminosities of the linear colliders are assumed to be  $500$ ,  $1000$ , and  $1000 \text{ fb}^{-1}$  for  $\sqrt{s}=500$ ,  $1000$ , and  $1500 \text{ GeV}$  respectively. The lower right hand plot “LET” refers to the case where no vector resonance exists at any mass in strong  $W_L W_L$  scattering.

scattering cross-section will have a smaller systematic error at an  $e^+e^-$  collider than at the LHC. In addition, an  $e^+e^-$  collider does an excellent job measuring the lowest order parameters of the chiral lagrangian for a strongly interacting gauge boson sector, as well as the technipion form factor for the pair-production of longitudinally polarized  $W$  bosons. Finally, an  $e^+e^-$  collider can provide unique access to the process  $W^+W^- \rightarrow t\bar{t}$ .

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